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Fabricating materials from living organisms: An emerging design practice

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ABSTRACT

Biotechnology offers exciting opportunities for novel and more sustainable alternatives for the design and manufacturing of products. One of the most promising approaches is the fabrication of materials from living organisms, such as fungi and bacteria. An increasing number of designers are engaging in this *Growing Design* practice, exploring the unique potentials of the grown materials for product design. In Growing Design, designers operate in interdisciplinary contexts, engaging in early stage material developments. Despite the widespread interest towards Growing Design, no systematic study has been conducted so far to understand how this practice unfolds and its contribution to the progression towards cleaner production. To this end, eight recognized professionals in the field were interviewed. The results illustrate how the conception of materials in design evolves when designers co-perform with biological organisms. This alters how the design process unfolds and the mindset adopted in design practice, shaping a novel, systemic vision on production and consumption practices. The paper further discusses the need for developing new sensibilities to face complex interdisciplinary problems in Growing Design and highlights the role designers can take in developing new materials for sustainable production.

1. Introduction

The role of product designers in contributing to a cleaner system of production has long been emphasized by scholars in the field of sustainability (Thackara, 2006; Manzini, 2009; Ehrenfeld, 2008; Brezet, 1997; Vezzoli, 2003). Many of the choices made during the design phase can determine the environmental impact of a new product. For example, designers can strategically choose to minimize the amount of materials involved in the product design; they can aim to design for easy disassembly and favor recycling; or to extend the product life cycle by planning its reuse and second-life (Ashby, 2012; Bocken et al., 2016; Bakker et al., 2014). Alongside these strategies, the selection of sustainable materials is regarded as central to improve the environmental performance of products (Ashby, 2012; Vezzoli, 2014; Karana, 2012; Zarandi et al., 2011; Sierra-Pérez et al., 2016). An increasing number of alternative materials are thus being developed and explored for sustainable design and manufacturing (Ashby, 2012; Prendeville et al., 2014). These alternatives include: 1) materials from *renewable* resources, i.e. *"with an acquisition rate inferior to their regrowing speed"* (Vezzoli, 2014, p.113); 2) *recycled* materials, i.e. obtained from reprocessing resources that have been already embedded in products (Vezzoli and Manzini, 2008; Lou and Mativenga, 2017); 3) *revived* materials, i.e. produced from discarded resources of industrial streams of production (for example agricultural waste) that are commonly not employed for industrial manufacturing (Sauerwein et al., 2017; Pacelli et al., 2015).

Alongside these sustainable material options, novel important opportunities come from biotechnology and biofabrication. Biofabrication is the process of producing complex materials and artifacts through the growth of living organisms and cells (Mironov et al., 2009; Pavlovich et al., 2016; Fujii et al., 2016), originally developed for biomedical purposes. Potential applications of this technology span from the biomedical industry (e.g. organ printing) to energy production (e.g. biofuels from algae), as well as the development of sustainable materials for manufacturing (Mironov et al., 2009). In the latter, biofabrication is considered particularly efficient when compared to other material production technologies, because it does not demand the extraction of valuable, virgin materials from the Earth's crust. Instead, biofabrication can use *renewable* resources as feeding elements for the living organisms (Holt et al., 2012; Lelivelt et al., 2015). In addition, biofabrication

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involves a limited amount of additional energy, because it harnesses the metabolic skills of growing biological systems to produce materials (Jones et al., 2017; Jiang et al., 2013). The resulting materials are not only harmless to the environment and biodegradable, but they can even nurture the cultivation of new materials in their end of life. For these reasons, biofabrication can be considered a highly sustainable replacement for fossils-based materials technologies, in line with a Cradle-to-Cradle approach (McDonough and Braungart, 2010). Examples of biofabricated materials are mycelium-based composites, which are produced by growing the complex network of fungal hyphae (i.e. the mycelium) on a substrate of waste resources. These composites have recently obtained the Gold Cradle-to-Cradle certificate (http://www.c2ccertified.org/products/scorecard/mushroom_material) and are often listed as one of the most promising alternatives to synthetic disposable materials, e.g. Styrofoam (Holt et al., 2012).

Beyond these clear environmental advantages, biofabricated materials offer a new spectrum of functional possibilities. With relatively simple variations in the fabrication process, e.g. changing the nutrients provided (Lelivelt et al., 2015; Camere & Karana, 2017), it is possible to achieve materials with very different properties, varying from thin, leather-like materials to bulk material composites (Fig. 1). Furthermore, under specific conditions, the materials have the ability to self-bind (Jones et al., 2017; Lee, 2011) or to grow directly in the shape of a product (e.g. Benjamin, 2014; López-Nava et al., 2016).

Fascinated by these novel opportunities, designers are increasingly getting involved in the development of these novel materials, often with techniques of their own invention (Rognoli et al., 2015; Myers, 2012; see for example the work of Suzanne Lee with bacterial cellulose, Lee, 2011; and the exhibition Fungal Futures, Montalti, 2016). This emerging material design practice is defined as *Growing Design* (Montalti, 2010; Ciuffi, 2013; Camere & Karana, 2017), which entails growing materials from living organisms to achieve unique material functions, expressions, and sustainable solutions for product design. Related literature has described its most representative cases, highlighting some of its central questions (Myers, 2012; Ginsberg et al., 2014; Collet, 2017; Rognoli et al., 2015). Despite the rising interest around Growing Design, no systematic study has been conducted to date to reveal the main traits of this emerging practice at the intersection of biology, crafts and design. Yet, understanding this practice is relevant to demonstrate the role design can take in early-stage development of environmentally sensitive materials and how this emerging practice can be supported and widely applied to contribute to cleaner production. The aim of this paper is thus to provide an understanding of how Growing Design practice unfolds. This knowledge will set an agenda of future directions for design professionals and researchers in the specific domain. To this end, we conducted eight in-depth interviews with design professionals who are experts in growing materials for design purposes. In the next section, we first provide a brief overview on how sustainability concerns are traditionally involved in material decisions related to design, and how designers increasingly engage in 'materials design' rather than 'materials selection' (Section 2). Subsequently, we provide a definition of Growing Design in relation to other approaches at the intersection of biology, materials science and design (Section 3). Section 4 describes the main activities of designers who grow materials for design purposes. We then introduce the interview study (Section 5) and the results obtained from the interviews (Section 6). The results are discussed in the remainder of the paper to highlight how Growing Design can contribute to a rethinking of the current system of product design and manufacturing (Section 7).

Fig. 1. Two examples of materials derived from living organisms. Left: thin, leather-like bacterial cellulose. Right: bulk mycelium composites.

2. From materials selection to materials design

Traditionally, designers select materials to materialize their product concepts (Ashby and Johnson, 2002). Increasing numbers of sources comprise 'sustainability concerns' to inform material decisions. These include, for example, strategies and guidelines to select environmentally sensitive materials (see e.g. Zarandi et al., 2011; Sierra-Pérez et al., 2016; Prendeville et al., 2014), methods to evaluate the sustainability of a selected material (e.g. the Eco Module of CES Material Selector by Granta Design: https://www.grantadesign.com/), or overviews of critical materials (Ashby, 2012; Peck, 2016). Moreover, a wide range of sustainable alternatives to conventional materials is today included in material databases and libraries, such as Material ConneXion (https://www.materialconnexion.com/) and Materia (http://materia.nl/), providing detailed information on their performances and environmental advantages. Recently, few dedicated initiatives have emerged to inform designers about materials that have a high sustainable value, both in terms of environmental and societal impact (e.g. Future Fabrics Expo, http://www.thesustainableangle.org/, or the Nike Making app, Nike, 2015).

Beside conventional materials selection and use, designers have started to occupy new spaces of intervention that are normally destined to other disciplines, e.g. materials science, biology and chemistry (Miodownik, 2007). They engage in activities such as materials testing or early stage prototyping, to inform the design and development of novel materials. In these projects, designers operate at the intersection of different disciplines, collaborating with several experts and integrating contributions from different disciplines, thus taking an interdisciplinary research approach (Sakao and Brambila-Macias, 2018; Wilkes et al., 2016). The value of these collaborations has been demonstrated for example in the development of the next generation of smart materials (see e.g. Light. Touch.Matters project: http://www.ltm.io.tudelft.nl/), showing how designers use hands-on activities to explore the boundaries of underdeveloped materials (Barati et al., 2017; Vallgårda and Sokoler, 2010).

Beyond these collaborations, designers have also started to engage in the self-production of materials with the goal of developing new sustainable alternatives (Rognoli et al., 2015). These novel practices have been described by Rognoli et al. (2015) through the notion of *Do-it-yourself (DIY) materials*, i.e. *"created through individual or collective self-production practices, often by techniques and processes of the designer's own invention"* (p. 692). In these practices, the role of designers radically changes from 'passive recipients' of fully developed materials, to 'active makers' of new material proposals (Karana et al., 2015). This active engagement in materials fabrication extends designers' control over product sustainability, as they can better handle materials' sourcing (e.g. favoring local, unused raw materials), their application in products (e.g. reducing amount of materials and waste) and end-of-life stage (e.g., crafting unique, non-repeatable aesthetics that stimulates users' emotional attachment to products) (Rognoli et al., 2015; Karana et al., 2017; Chapman, 2015). DIY materials practices are thus profoundly motivated by a rising drive to design for sustainability; often, they are triggered by the recognition of a potential in discarded yet valuable resources in the waste streams of production (i.e., *revived* resources, Sauerwein et al., 2017; Pacelli et al., 2015). An example is the project 'Forest Wool' (http://www.tamaraorjola.com/), in which the designer developed a collection of materials and artifacts from discarded needles of pine trees, which are cut down annually for the production of timber. This example also shows how, through hands-on experimentation, designers are able to explore new possibilities for materials, developing several variants that differ in functional or expressive qualities. In other words, in DIY material practices, designers consider materials less as 'given' and 'known' entities, and more as a set of potentials which can be adapted, shaped and fine-tuned toward a specific product application (Manzini, 1986). Growing Design is situated among these DIY materials practices, further extending designers' intervention over the biological processes of materials formation.

3. When biology meets design

Growing Design arises from a context of several approaches that cross-fertilize biology and design (Myers, 2012). In a recent publication (Camere and Karana, 2017), we have grouped these attempts under four categories: (1) augmented biology; (2) biodesign fiction; (3) digital biofabrication; (4) growing design (Fig. 2). Many recent design cases which demonstrate these intersections between biology and design are listed in Fig. 2. For reasons of space, only few representative projects (number 4, 5, and 8 in Fig. 2) are explained in detail, motivating the differences and commonalities of each specific approach.

In ***augmented biology***, designers seek the re-engineering of cells to design new biological organisms that can help us cope with contemporary societal challenges, such as famine, diseases and energy shortages (Collins, 2012; Agapakis, 2013; Ginsberg et al., 2014). An example of augmented biology is the project *E. chromi* (Ginsberg, 2009), a self-diagnosis toolkit employing an engineered strain of Escherichia coli, which, once ingested by the patient in the form of a probiotic drink, can secrete pigments in response to the detection of diseases and prompt people to early self-diagnosis.

In another project from Ginsberg (2013), '*Design for the sixth extinction*', the designer undertook a speculative design approach (Dunne and Raby, 2013) to envision how biology can be useful in future, provocative scenarios. Ginsberg (2013) explores the possibility to design new biological organisms that could maintain and revive disappearing ecosystems in a post-apocalyptic future caused by the effects of human agency over nature. In this approach, defined as ***biodesign fiction***, designers aim at debating the implications of biotechnological futures before they happen (Ginsberg et al., 2014): the outcome of design is therefore a speculation, a scenario, or an '*experiential prototype*' (Buchenau and Suri, 2000) designed to make people interact with the envisioned future.

In other cases, designers couple biological tools with advanced computer technologies, in a ***digital biofabrication*** approach (Camere and Karana, 2017). For example, researchers from the Mediated Matter Lab developed a water-based fabrication method to 3D-print biomaterials, harnessing the growth of microorganisms to complete the form of the printed structure (Bader et al., 2016). In this approach, designers use advanced computational tools to 'hack' the biological systems. Their design process is thus highly influenced by such tools.

Compared to the approaches listed above, the fourth approach, ***Growing Design*** (Montalti, 2010; Ciuffi, 2013; Camere & Karana, 2017), is characterized by a hands-on practice, focusing on the development of novel materials for product design. The outcome of this process is often realistic, to be applied in consumer products in the near future. Designers who grow materials do not seek for solutions given by synthetic biology and they employ unmodified biological organisms. In the following section, we elaborate on this approach further by providing three material cases in detail as illustrative cases of growing design.

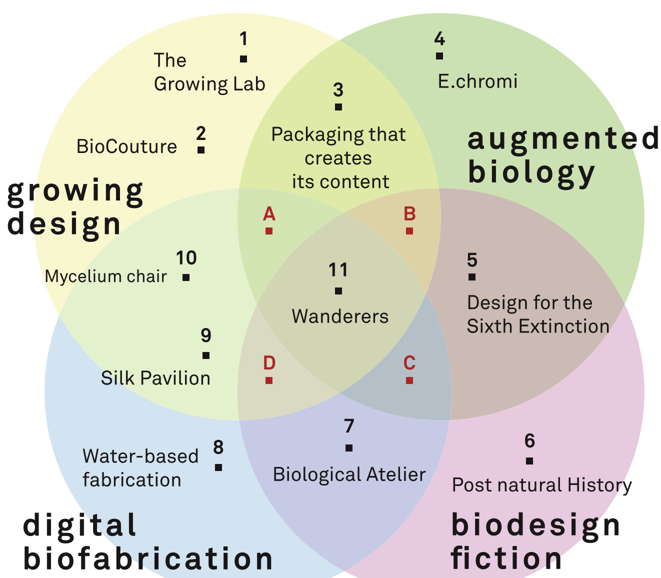

Fig. 2. Four approaches cross-fertilizing design with biology and related cases: 1) materials and product from mycelium (Montalti, 2010);2) a collection of garments from bacterial cellulose (Lee, 2011); 3) a packaging grown by engineered bacteria that also produce its content (Lim & Carey, 2013); 4) self-diagnosis toolkit employing engineered Escherichia coli (Ginsberg, 2009); 5) Engineered organisms to revive ecosystems in speculative future (Ginsberg, 2013); 6) luxury fashion items for 2080 grown by biocells (Congdon, 2013); 7) Speculative encyclopedia of new living species (Fournier, 2012); 8) biomaterials fabricated through additive manufacturing (Mediated Matter MIT Lab, 2014); 9) digitally fabricated structure completed by silkworms (Mediated Matter MIT Lab, 2013); 10) 3D printed chair completed by mycelium (Klarenbeek, 2013); 11) bio-augmented wearables for extreme planetary environments (Oxman, 2014).

4. Growing design: mycelium, bacteria and algae as illustrative cases

Recent design exhibitions have showcased several Growing Design projects (Fig. 3a and b): e.g. a plastic bottle made from algae (Ari Jonsson at Dutch Design Week, 2016; Morby, 2016), and a dress composed of modules of pure mycelium (Aniela Hoitink at Fungal Futures; Montalti, 2016). Many different biological organisms can be employed by designers to grow materials and products, e.g. *amoebas* (Fig. 3d, Shamees Aden, 2012; Collet, 2013), envisioned for the growth of fit-to-size athletic shoes; or *slime molds*, to design optimized shapes (Fig. 3c, Nakagaki et al., 2000; Moisy and Pschetz, 2017).

Interestingly, Growing Design can also be seen to share techniques and finalities with other contemporary design and production practices that involve natural materials, such as wood or plants. For example, the UK company 'Full Grown' grows willow trees into the shape of chairs over the course of seven years (Fig. 3e; http://fullgrown.co.uk/). Similarly, in the project 'Modular Lagenaria Gourds', the designer Andrew Mowbray has envisioned the cultivation of gourds as architectural modules (Fig. 3f). The two projects have many similarities with the textile grown by plant roots, designed by Diana Scherer (project 'Interwoven', Fig. 3g). In all three cases, designers focus on controlling the *shape* in which the living system grows (the tree or the plant), thus affecting the structure of materials, but not the materials ingredients (Rognoli et al., 2015).

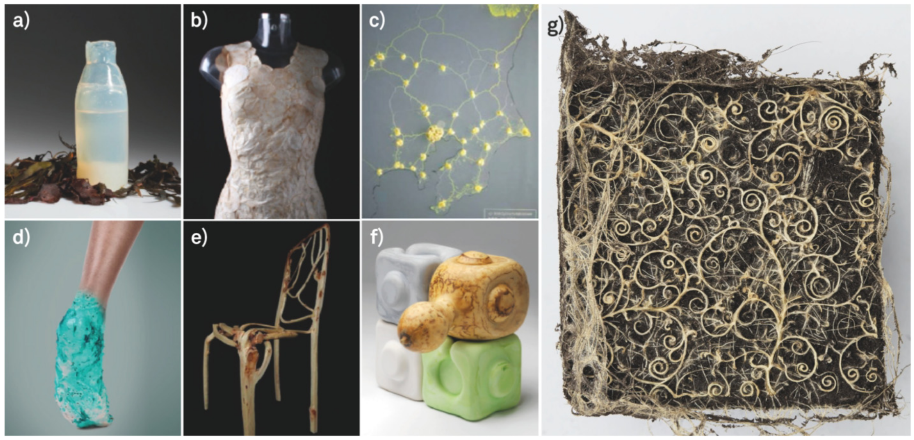

Fig. 3. From top left: a) Algae Bottle, Ari Jonsson; b) MycoTEX, Aniela Hoitink; c) Tokyo transportation map (Nakagaki et al., 2000). Bottom row, from left: d) Amoeba Trainer, Shamees Aden; e) Chair, Full Grown UK; f) Modular Lagenaria Gourds, Andrew Mowbray; g) Interwoven, Diana Scherer, NL.

The majority of projects falling under the Growing Design concern materials derived from the following groups of biological organisms: fungi (specifically, mycelium, the vegetative part of fungi), bacteria and algae. The fabrication of materials from these organisms follows similar action steps, which are articulated below.

Mycelium-based materials can be produced either as pure materials from liquid cultures of mycelium (Haneef et al., 2017; Montalti, 2017) or as composites based on organic substrates (Holt et al., 2012). The majority of designers work with mycelium composites, as the process of fabrication is relatively more stable and accessible than that of pure mycelium. The process starts by inoculating a strain of fungi in a substrate of organic substances (Holt et al., 2012). The fungus then grows by digesting the substrate (e.g. rapeseed straws) and forming a solid network of mycelium around it, constituting a bulk material that is covered by a white, soft skin (Jones et al., 2017). The substrates used to grow mycelium-based composites are normally retrieved from industrial or agricultural waste streams, like wheat or rice straw, wood sawdust or other fibers, e.g. flax and cotton (Jiang et al., 2013; Lelivelt et al., 2015). The preparation requires a certain level of sterility to achieve appropriate results and prevent contamination by other organisms (Jiang et al., 2013). By varying the nutrients and 'recipes' used to fabricate the materials, designers can achieve composites that significantly differ in their technical and *experiential performance* (Karana et al., 2015). The materials can take two to four weeks to grow, depending on the volume. After the growth, low-temperature drying is required to deactivate the living organism. Alternatively, materials can be maintained at room temperature, preserving the possibility of future growth and self-binding abilities (Jones et al., 2017). The whole process can be handled with very limited amount of energy and water, eventually employed only during the growth and drying stages and it requires only low-cost, waste materials that can be sourced locally (Jiang et al., 2013; Jones et al., 2017; Holt et al., 2012). For these reasons, mycelium-based composites, such as the ones commercialized by Ecovative, obtained a Gold certification on a set of sustainability criteria established by the Cradle-to-Cradle Product Innovation Institute (http://www.c2ccertified.org/products/scorecard/mushroom_material), such as material health, material reutilization and renewable energy and carbon management.

To grow materials from bacteria, as for example bacterial cellulose, designers follow similar action steps. Materials grown from *bacteria* are mainly developed as thin, flexible materials, for example to replace animal leather (e.g. BioCouture by Suzanne Lee; Lee, 2011). The production of bacterial cellulose occurs by the fermentation of a symbiotic culture of bacteria with yeasts in an acidic nutrient medium (pH = 3), containing monosaccharides like glucose, fructose or glycerol (Iguchi et al., 2000). When provided with the correct nutrients and growing environment, some species of bacteria produce a layer of 100% pure cellulose (Lee et al., 2014; Ross et al., 1991; Huang et al., 2014; Ng and Wang, 2016). This is potentially interesting compared to animal- or plant-based cellulose that amount to 40–60% cellulose content, thereby containing also other elements, such as lignin, that are difficult to process and require large amount of energy. The growing process can be carried out in static or agitated (i.e. machine-shaken) cultures, and can take up to four weeks to form a sufficiently thick layer of cellulose (Iguchi et al., 2000). As for mycelium, the fabrication process requires a certain level of sterility to prevent the contamination from other competing organisms or fruit flies, attracted by the sugary environment. The growing process is stopped by washing the cellulose sheet in soapy water (Lee, 2011); immediately afterwards, the material is dense with water and requires drying, before acquiring its real qualities in terms of color, thickness and surface appearance (Lee, 2011). The configuration of nutrients, organism and growing environment used for the fabrication process heavily influences the properties of the final materials, which can thus range from thin paper-like cellulose to thicker, leather-resembling materials (Huang et al., 2014; Lee, 2011). As in the case of mycelium-based composites, the production of bacterial cellulose can be handled by using almost no additional energy and by using sustainable resources, and it is therefore considered to have large potential in replacing animal- or plant-based material production systems (Lee et al., 2014; Jang et al., 2017).

In summary, the fabrication of bacterial cellulose and mycelium-based materials, albeit entailing different biological processes, follow very similar action steps: 1) a *preparation* phase, where designers set the conditions for the materials' fabrication; 2) a *growing* stage, in which the organism fabricates the material; 3) a *drying* phase, to deactivate the organism and achieve the resulting material; and eventually, 4) the final *shaping* of the material through different techniques. These phases are common for all fabrication processes and allow different spaces of design intervention: by tweaking the variables of each phase, designers can achieve materials with varying properties. The process of fabricating materials from *algae* is instead slightly different. In this case, the fabrication process starts either from micro- or macro-algae (Koller et al., 2012; Hannon et al., 2010). Although some species are suitable for indoor cultivation (Richmond, 2008), in most cases designers working with algae prefer to collect the ones accumulating on seashores, drying and processing them with various techniques in order to extract their sub-components (e.g. agar-agar or cellulose fibers). Hence, designers do not directly engage in the growth of algae, and their practice is therefore more similar to a conventional DIY materials approach (Rognoli et al., 2015). Despite this difference, the discussion of algae-based materials projects alongside cases of Growing Design is very common (Myers, 2012) and can be motivated by few reasons (Camere and Karana, 2017). Algae offer a promising and almost inexhaustible resource that can be processed to extract biofuels, electricity, cellulose, alginates (useful as binding agents) and other components with many potential applications (Wijffels et al., 2013; Richmond, 2008; Priyadarshani and Rath, 2012). Many species of algae have an impressive rate of growth (Bold and Wyynne, 1978) that qualifies algae as a highly efficient system, beyond 'renewable' resources (Vezzoli, 2014). Moreover, the indoor cultivation of algae currently entails few environmental disadvantages, among which the use of large amounts of electricity or the loss of the bioremediation potential that algae have for oceans (Raja et al., 2008; Richmond, 2008; Gonçalves et al., 2016). For this specific reason, designers currently do not engage in the self-production of algal materials. Nevertheless, as research explores more efficient systems of cultivating algae indoors (Podola et al., 2017), we expect that designers will start growing algae in the near future. These arguments suggest the inclusion of algae-related cases in our definition of Growing Design.

As shown, these novel production technologies have considerable environmental advantages; yet, they also present few limitations which might hinder a widespread application. Specifically, the materials are particularly sensitive to water and highly perishable, characteristics that, on the one hand, favor their biodegradation; on the other hand, these characteristics have so far constrained their application to single-use products (e.g. packaging, Holt et al., 2012). Nevertheless, given the early stage and potential of these materials, current research efforts are being devoted to improve the materials' durability and promote their use in other product applications, with extended life cycles. The interviews narrated in the next sections will show how designers deal with the materials' advantages and limitations and how their explorations can contribute to unveil the potential of these emerging materials technologies.

5. An interview study with designers who grow materials

Designers participating in the interview study were selected based on the given definition of Growing Design. The purpose of the study is to investigate the implications of growing materials from living organisms for product design and manufacturing. To understand this emerging material practice, it is important to elucidate the specific mindset (i.e. motivation, approach) and skillset it mobilizes and what it shares with crafts, science and engineering. To this end, we approached professional designers who challenge themselves with the growth of living organisms for product design purposes.

As the specific domain is novel for design practice, it was not possible to adopt the conventional standards of *design expertise* for the selection of participants (e.g. Cross, 2004; Lawson and Dorst, 2013). Thus, indicating whether participants can be considered as experts or novice designers is rather difficult. However, from a recent analysis of design cases we concluded that these materials required a minimum of a year for a designer to become familiarized with the material fabrication to its full extent (Camere and Karana, 2017). We thus selected product designers who have been working with biological organisms for at least one year, with a practice corresponding to our definition of Growing Design. For example, we excluded cases that involve the use of digital fabrication or that have a speculative nature. The selected participants actively engage in the growth of materials and products from fungi, bacteria and algae, listed as the most common organisms employed in Growing Design. Some of the participants have worked with multiple biological organisms; however, participants were recruited for their expertise on one specific type of material. Table 1 summarizes participants' experience in Growing Design in terms of materials and organisms used and years of expertise; grey shading indicates the biological organisms for which they are considered experts. In total, we interviewed eight Europe-based professional designers, of which three are experts of materials derived from fungi, two are algae-based materials experts, and three, bacteria-based.

5.1. Method

The interview method followed a semi-structured approach, asking a list of predetermined questions while allowing the exploration of emerging topics (Breakwell, 2006; Denzin and Lincoln, 1994). On a few occasions, we used diagrams to trigger specific answers from participants, as the process of graphic elicitation is proved to be a useful means to convey contributions from interviewees that are otherwise difficult to verbalize (Umoquit et al., 2008; Crilly et al., 2006). The interviews were structured around three main phases, to foster the progressive deepening of the conversation. The first phase covered questions related to the *material* itself, such as: *"what is the material you worked with? How would you describe it? How long have you been working with it?"* In the second phase, we aimed to discuss how their design process unfolds. To prevent vague and fuzzy answers to these questions, we asked participants to visually represent the process of designing with this material, while thinking aloud. We then used the diagrams produced by participants to ask more detailed questions related to the process described, e.g.: *"How does the phase of idea generation unfold? How do you structure it? Did you involve a user study? When did the idea/concept come into this process?"* We gave another diagram to the interviewees (Fig. 4) and asked them to define their own practice in relation to the listed disciplines (e.g. craftsman or biologist). We asked specifically: *"How much (on a scale from 0 to 5) do you think you share with these disciplines in your design practice?"*. Lastly, the third phase of the interview focused on their motivations.

A total of eight interviews were conducted, of which five took place as studio visits and three over video-conference; all interviews were performed in English. The five interviews performed in designers' studio allowed documentation of samples, tools, and work environments involved in the practice of Growing Design (Fig. 5). The interviews were audio-recorded and subsequently transcribed. The audio-records of interviews were transcribed taking note of participants' actions (e.g. picking a material sample) and non-verbal expressions (e.g. laughing). Interview results were analyzed using thematic analysis, according to which transcripts

Table 1
Expertise of each study participant.

	Fungi	Algae	Bacteria	Years of expertise (In growing design)
Designer 1 (D1)	x			1 year
Designer 2 (D2)	x	x		10 years
Designer 3 (D3)	x		x	6 years
Designer 4 (D4)		x		3 years
Designer 5 (D5)		x		3 years
Designer 6 (D6)			x	10 years
Designer 7 (D7)	x		x	4 years
Designer 8 (D8)			x	6 years

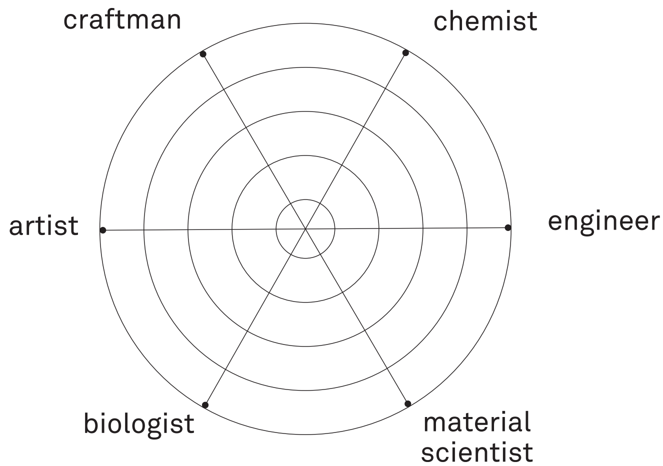

Fig. 4. Diagram used to explore designers' definition of Growing Design practice during the interviews.

are first divided into segments and coded. For coding process, we adopted in-vivo approach, using participants' own words to label each segment (Saldaña, 2015).

6. Results

The interviews lasted approximately 50 min per participant. Coded answers led to the emergence of categories (i.e. repeating patterns, Saldaña, 2015), which were subsequently grouped and organized according to four topics: *Grown Materials, Growing Design process, Growing designer and Growing Design vision* (Fig. 6).

The first group, i.e. 'Grown Materials' depicts answers defining the unique characteristics of growing materials according to our participants. These characteristics influence and shape the way designers work with living organisms. The second topic, 'Growing Design Process', describes how, for example, growing a material from living organisms entails a bottom-up approach, starting from understanding the material through tinkering and controlled experiments (see 6.2.4 and 6.2.5). Moreover, interview results also

Fig. 5. Pictures of the interviewee's studios, taken during the interviews. From top left: samples of mycelium-based materials; samples of bacterial cellulose; bags of grown mycelium; samples of algal materials.

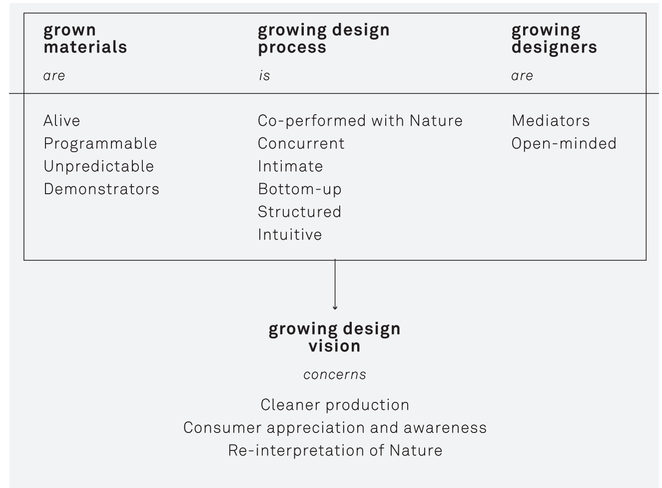

Fig. 6. Categories and themes that emerged from participants' answers in relation to the interview topics.

bring insights on how these particular designers are, for example, mediators of multiple disciplines (Topic 3, 'Growing designers', 6.3.1). The specific characteristics of Growing Design, listed under these themes, have implications for the way designers envision the futures of design and manufacturing (Topic 4).

All categories were found relevant across the use of fungi and bacteria, while in the case of algae, categories related to the growth and aliveness of biological organisms did not emerge as significant. For example, participants did not describe their process as 'co-performed with Nature' or as 'intimate' (Fig. 6, 'Growing Design Process'). However, several other important categories also hold true for algae, such as the 'programmability' of the material (Fig. 6, under 'Grown Materials') or the need for the designer to act as 'mediator' of other disciplines (Fig. 6, under 'Growing Designers'). Particularly, we observed that working with algae has the same implications for designers' visions over the future of manufacturing, consumption and Nature (Fig. 6, 'Growing Design Vision'). In Section 4, we argued that these designers do not engage in the growth of algae because, at the moment, technologies for indoor cultivation have severe environmental limitations. One of the participants' answers brings further evidence of this: *"It's my goal not to really harvest the algae from the sea, but to collect as much as possible what's washed the shore, to not really interfere with their natural habitat"* (D5). While it is possible to speculate that with novel cultivation methods the differences with other Growing Design practices will blur, through our results it is only possible to maintain the due distinctions in the inclusion of algae as a case of Growing Design. In the following sections, we will present each category with excerpts from the interviews.

6.1. Grown materials

The first topic covers how participants describe the material outcomes of Growing Design. Materials are depicted as: 1) alive; 2) programmable; 3) unpredictable; 4) demonstrators.

6.1.1. Alive

Immediate descriptions that designers give about their materials are related to the 'aliveness' of the organism, which has an agency of its own:

> "(…) *it's really, it's a stubborn thing you know, it has its own way of doing things.*" (D6)

This results in some *unique experiential qualities*, which are dictated by nature and are described by designers as unique due to materials growth from living organisms. For example, these materials often have a unique odor:

> "*the materials are not yet fully perfected, and I actually like that, so they have a smell. … It's not a terrible smell, but they do have a smell, and that smell - it's what confuses people. it's like … it smells like forest. So hardly polyurethane can smell like forest* (…)" (D2)

6.1.2. Programmable

Designers can steer and control the material growth to obtain variable material properties. The participants describe how widely the materials can vary according to the 'recipe' they use:

> *"there are different ways in which you can use the seaweed, every treatment gives a different color. (…) there are thousands of options I think, but with boiling, you can blend it, you can put a whole plant in, it's … lots of different processes, and it gives a different end result of color in the end."* (D5).

6.1.3. Unpredictable

At the same time, living organisms are highly non-linear in their response (Chen and Crilly, 2016). This can significantly alter the result of experiments from what is expected by designers:

> "*I never know what I'm going to get, when I open it, it is always a surprise, always intriguing … It can be painfully frustrating, because you figure out you need more lab time, to find out how to control this thing. And that can be a very expensive process {laughs}. I make these stencils, that effectively are the petri dish, and I spent a lot of money doing that and … it didn't even work.*" (D8)

6.1.4. Demonstrators

Lastly, the interviewees' answers show how products and materials act as demonstrators of the potential of this novel approach to material, design and manufacturing:

> "*… the vases were just an excuse. They were an easy way 'in', for letting some material becoming something understandable, for going beyond the fact of* [grabs a sample], *mmm, okay, it's a material. it's like, okay, I see a function. I see something there.* (…) *let the material express* (…) *but don't try and make something complex, just make it as simple and as primitive, as the material looks like* (…) *a primitive volume. So, the idea of the archetypical object.*" (D2).

6.2. Growing design process

Designers delineate the process as: 1) co-performed with Nature; 2) intimate; 3) bottom-up; 4) structured, yet 5) intuitive.

6.2.1. Co-performed with nature

As mentioned earlier, the material outcomes of designers' experimentation are often mediated by the agency of the organism. Thus, designers perceive the process as co-performed in cooperation with Nature, describing organisms not only as co-makers (Collet, 2013), but also as co-designers of the final product.

> "*I think it's a co-creation. I think it's a better word. A co-creation of me as designer and the organism, slime mold* (…) *but I was also interested to see if an organism could design something for you, based on its biological algorithm.*" (D6)

Designers emphasize that in growing materials they do not participate in the actual 'making' of the material. Instead, they wait and observe what the biological organism will offer. These observational moments are necessary to inform their understanding of the organisms' behavior:

> "*that's the thing about working with living materials, because once you have prepared everything* (…) *now you have done your bit, and he has to do his bit … you just set the conditions for growth, and then you just watch it grow, or not* [laughs] (…) *I'm used to grow plants, it's sort of a natural, normal thing to do.* (D3)"

In addition, in several interviews, designers compare Growing Design to some established social practices, which require biological growth, such as harvesting or baking bread:

> "*… because you know we have been growing beer, making bread for thousands years, and mycelium for me it's alongside that, exactly* (…) *if you look at linen, for instance … It was a plant that was grown, and cut, and harvested and then you extract the linen … It's kind of a similar process, except that you grow a fiber, as opposed to material or fabric.*" (D3)

6.2.2. Concurrent

These materials yield few unique production opportunities owing to their aliveness, hence grow-ability of the organism. They can be grown directly as a semi-developed or into the shape of a product, *"symbiotically producing the material and the product together"* (Camere and Karana, 2017, p. 110) to achieve a *concurrent* production (Karana et al., in press). Moreover, until their growth is stopped, they have self-healing abilities that can become handy during the fabrication process:

> "*it's really intriguing to be confronted with* (…) *kind of self-healing materials, it's the magic of when you produce one piece, but then during the production phase the piece breaks but it's still wet, and it's still alive, all you have to do it's to put it back together and let it grow for few more days, and it will just come back together. and that's quite magic, it's definitely something you cannot achieve with synthetic compound*" (D2).

6.2.3. Intimate

The process of watching the organism grow into a material is associated with the experience of having a pet, i.e. looking after another living being:

> "*you have some feelings, you have something, actually, activating, into you in terms of engagement.*" (D2)

> "*I found that it brings a level of intimacy with the material, because you have looked after it as it grows, so you care for it even more, because you have grown it. It's a level … of emotional, intimate level that you would not necessarily get …*" (D3)

Therefore, the Growing Design process is characterized by a rich and intimate emotional experience. This visceral bonding, established with the material through the process of growth, makes designers attribute a higher value to the grown material:

> "*I have got some very beautiful samples … But I am having problems, a lot of them are getting infected, which is infuriating* (…) *You could see it slowly dying. And again I had this sense of working with something living, and so you have a sense of death* (…) *that also brought a new dimension that I never encountered before, working with these new materials* (…) *What I found really interesting in*

this, that because I grew the materials, they became very very precious materials, because I didn't have a huge quantity to play with (…) *even if you buy very expensive piece of fabric … You think it's expensive, but in terms of the material, the cost, but not in the sense of emotional investment you have had in growing that thing.*" (D3)

6.2.4. Bottom-up

Growing Design entails a bottom-up, material-driven approach, *starting from understanding the materials at hand* (Karana et al., 2015). In the case of Growing Design, the 'materials' at hand are the abilities and needs of the microorganism, stimulating designers to tinker with different ingredients (e.g. substrate, additives, etc.) and find a way to control the material's growth:

"… *I had to understand what my microbe is … where it normally lives, where do we normally find it, why is it competitive in that space, what are the genetic pathways that have given way to this pigment, how can they be mediated.*" (D8)

Hence, a large part of the process is dedicated to discovering techniques and tools to work with these materials:

"*it's a craft based process, with the material that though have [sic] no craft history. So you are kind of trying and defining the craft. Also, with the craft goes all the sets of techniques, methods that can be utilized for working with the matter.*" (D2)

As designers strongly invest in the fabrication of materials, they are scarcely keen on investigating how end-users (or consumers) would receive these materials.[1] They often ask for informal feedback from possible end users at exhibitions/design fairs, etc.:

"*I have never been very interested in asking what people think of the materials. The way I found out is to exhibit the work and see how people respond to it. But it's not a structured study as such, it's really, 'here, see what I've done … expose it, exhibit it, and see what people think'.*" (D3)

6.2.5. Structured

Materials produced in Growing Design are affected by multiple variables and are highly sensitive to changes in the fabrication process. For this reason, participants explain that their process is often structured with scientific protocols, trying to control and manipulate each experiment as scientists: "I structure my experiments according to an ambition. Sometimes I structure them around a keyword, so if I'm working on 'folding', for instance, I setup a whole range of protocols of folding, where the mycelium is holding the fold into place, for instance, or is creating the fold … So, I think about what kind of experiments I can do around that, and then I make sure I have the right molds, the right substrate, so it's just preparing everything we need to do that … (D3).

6.2.6. Intuitive

Nevertheless, designers also state the role of serendipity and intuition in Growing Design. In some experiments, they allow their gut-feelings to guide them and follow new ideas that come directly through making. In other words, they couple the scientific attitude with a more opportunistic approach toward experimentation:

"*I think the challenge is how you translate your creative intuition within a clearly defined set of circumstances within a laboratory, working with a living organism, that has specific conditions of growth, so yeah, you have got on one hand this protocol, and then you are trying to bend a protocol, so it can start to express the designers' hand, somehow, that's the challenge.*" (D8)

6.3. Growing designers

The third theme of answers reveals how designers define themselves in the practice of Growing Design. Specifically, they identify themselves as: 1) mediators and 2) open-minded.

6.3.1. Mediators

The interviewees frequently and commonly emphasize their role as mediators of multiple disciplines. Importantly, the designers express the need of collaborating with other experts, such as microbiologists and chemists. They stress that in Growing Design it is possible to achieve feasible, yet unique results only through the mutual effort of diverse expertise:

"*I think this whole biodesign movement is also something like what the Bauhaus was back then, different designers and artists collaborating, mycologists, physics, everyone together, everyone able to see each other's values, and I think if you want to make a good, or a product, you have to collaborate with each other.*" (D6)

By working in close collaboration with different disciplines, designers need to learn a new vocabulary, not only to understand scientists' know-how, but also to become autonomous in envisioning the possibilities of biotechnology for design practice:

"*I was just interested in understanding what this world is, how they talk, and then just by getting interested, you start growing, and then all of a sudden when you go and talk to a biologist, you're to be trusted, because you're talking the same language* (…) *And that's also an ability, which is very important to possess* (…)" (D2).

We had provided designers with a diagram (Fig. 4) to discuss how they consider their own practice in relation to, for example, craft, biology, etc.

Although we did not necessarily expect to find a common pattern, the diversity of their answers (Fig. 7) shows that designers experience difficulties in defining their practice: "*I never know how to define myself (…) I always let others give definitions" (D2).* Designers stress the need to know *"a little bit of everything"* (D8), maintaining their perspective of themselves as *generalists* (D2, D3, D8) rather than becoming specialists in a discipline. Nevertheless, Fig. 7 also depicts a dominant contribution of crafts in shaping designers' practice, on which most interviewees agreed. The role of biology and materials science are, in contrast, more controversial. When assessing how they feel to share with these disciplines, designers comment that they feel humbled to compare their knowledge to that of experts of such disciplines, thus they rated them lower than they would have wanted to do.

6.3.2. Open-minded

Designers also stressed the importance of an open-minded attitude toward experimentation and (design) research. This mindset helps them to see opportunities even in failed experiments, valuing results that are not necessarily in line with the initial

[1] Note that the Material Driven Design Method developed by Karana et al. (2015) suggests understanding material-people interrelationships, and bridging technical and experiential qualities of a material at hand in search of a meaningful material application. Application of the method in Growing Design is illustrated in a recent graduation project of Delft University of Technology (Blauwhoff, 2016; Karana et al., in press).

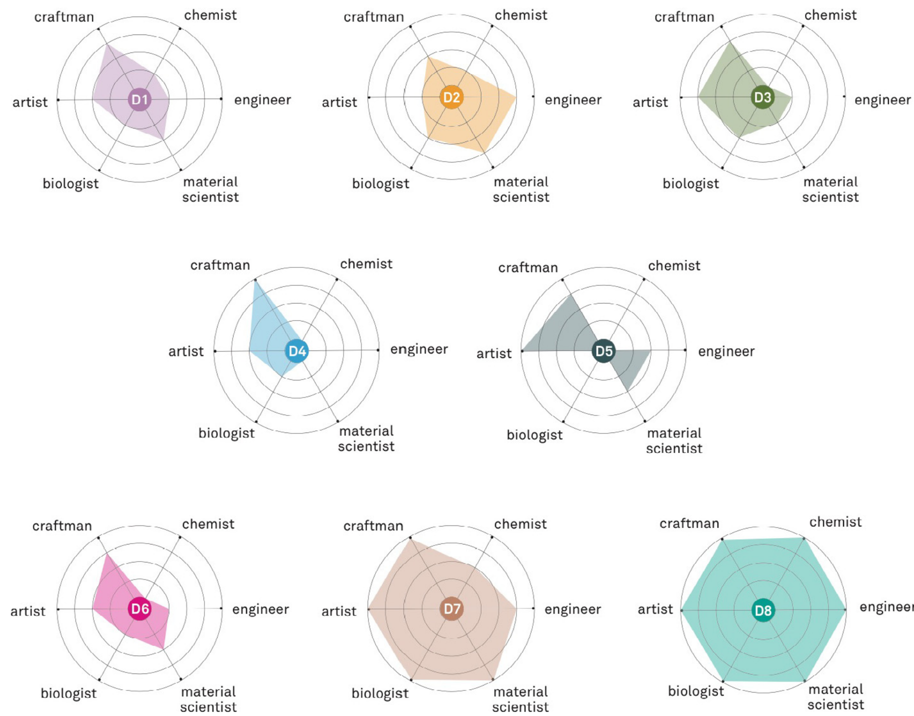

Fig. 7. Designers' answers in diagrammatic form, representing how each interviewee feels towards the listed disciplines.

research questions. To this end, they also consider themselves *radical* because they believe they alleviate or alter the rules of science:

> "(…) *okay, you are in the lab, that's how you grow things: don't grow it that way. Find your own way to grow things. Which is something very difficult for a scientist to start doing. That's what they are taught, and that's what they do* (…). *I was growing pure cultures for a project which was about plastic degradation. And then it happened that because I did an experiment in the wrong way, there was a certain growth happening* (…) *And then suddenly there was a pure material of mycelium. Which was like, 'wow, this is amazing'. And I remember the professor having the same surprise* (…) *But why does it happen? because you're just not respecting the rules. So, you're messing it up. And that's where … from that coincidence, potential innovation can arise.*" (D2)

By engaging with Growing Design and being in lab environments, designers also establish an open-minded approach toward emerging technologies, such as genetic modification of biological organisms:

> "*… you would love to just get a genetically modified organism and do something fantastic just to get things going, not so much to do that, because that's perhaps not viable, or not smart, or not good, just to make sure you can get something going, in the middle of this value chain.*" (D4).

6.4. Growing design vision

The Growing Design vision concerns: 1) cleaner production; 2) consumer appreciation and awareness; and 3) a reinterpretation of Nature.

6.4.1. Cleaner production

Through the growth of materials, designers come to envision the impact that biotechnologies could have on our current system of production:

> "*Really, if we could make, the way a cell multiplies and grows, if we could fabricate in this way, we would be really move on from the current mess.*" (D3)

> "*… the point is the cohesiveness and togetherness, and our awareness, of the responsibility towards all living things* (…) *What really drives me, is the fascination* (…) *for the fact that everything becomes something else and becomes beneficial for some other process, and that such phenomenon happens because of living systems and living organisms …*" (D2)

6.4.2. Consumer appreciation and awareness

Moreover, the interviewees also accentuate how their practice can affect the consumers' appreciation of materials, or create awareness about sustainability related issues in material and product design, production and consumption:

> "*What sense does it make that a garment can cost less than a sandwich? when we think about the resource and the energy, the time that has taken from being a ball of cotton, or a seed actually, how can that possibly cost … so my motivation is to look at this more pragmatically from a material perspective, to say OK, where do our materials come from? How do we begin to change people's perception about them?*" (D8)

Particularly, they describe their role in materializing the knowledge that resides in scientific laboratories, transforming it into tangible products that people can experience:

"*I felt the responsibility* (..) *to try and democratize somehow, the scientific knowledge and the scientific tool, bringing it out of the lab, allowing the everyday person or at least the attentive person, the interested person, to start getting acquainted with some notions, and start getting into the conversation* (…) [till] *society is fully involved.*" (D2)

"*Now, a lot of designers also become researchers, but I think they can initiate projects like these. Maybe they just give a slightly different point of view, and in the end they can communicate the outcome of the project to the public, and I think that's also very important, that it doesn't stay* [at the level of, sic] *scientific project, but the people understand what happened, and that it looks nice, and people want to understand it. And get involved.*" (D5)

6.4.3. Re-interpretation of nature

Finally, designers describe how growing a material makes them understand Nature differently, not any longer as something 'given' and immutable, but rather as something that is shaped and affected by human activities (Crutzen, 2002). They question the term 'natural' as opposed to 'man-made' and they see biotechnology as a means of integrating human activity into Nature in a more holistic way:

"*I think Nature is going to be* [understood] *on a new level, that used to be just a macro level, you know, you harvest your flax, and you make it into your clothing, but now also on a molecular level, we are going to make much more use of these systems that we used to do fifty or a hundred years ago. So I think Nature is going to be reinterpreted. And I think the awareness of this system is going to be … of natural systems, like carbon, flax, how these large movements of nutrients, building blocks, actually grow … that's the part where nature becomes very interesting.*" (D4)

7. Discussion

The interviews report the perspectives of designers who grow materials for design purposes. Their answers describe the unique characteristics of the *materials*, *process* and *designers* engaged in the practice of Growing Design, and the *vision* that is both the motivation and the end result of their practice. Although we present them as distinct, the categories of answers are interrelated and they mutually influence each other. For example, the resulting materials are *alive* and *unpredictable* because the process is *co-performed* with living organisms, and this collaboration entails a more *intimate* relationship between materials and designers. Likewise, designers start their process of design from understanding what their medium is, in a *bottom-up* approach. To do so, they need to become *mediators* of different disciplines and vocabularies, adopting the *structured* approach of science while allowing their *open-minded* attitude to steer more *intuitive* processes of exploration.

These interrelations are patterns in which materials (*grown*), taken as entry point, affect people's (*designers*') ways of doing (*growing design process*), in line with the framework proposed by Giaccardi and Karana (2015), which describes the active role of materials in shaping social and cultural practices. Specifically, in Growing Design, the characteristics of materials (i.e., being *alive, unpredictable, programmable* and *demonstrators*) directly influence the process of designing and producing, but at the same time, they mobilize new mindsets for designers (i.e., becoming mediators of multiple disciplines and open-minded). The analysis of these patterns between grown materials, process and designers elucidates few specific implications for the future of this emerging practice and design research at large.

7.1. Toward new design sensibilities

As interviews highlight (6.2.1), designers perceive their practice as *co-performed* with an organism that has an agency of its own. When working with living systems, designers negotiate the final form of an artifact with a highly responsive material — an *alive* one, which limits the intentionality of designers and makes the outcome *unpredictable*. Designers delegate the fabrication of the material to an 'invisible' biological organism, whose behaviors and technology is obscure to them. Hence, they experience novel challenges in understanding materials *"from the inside"* (Ingold, 2013). One of these is the temporal division between the moment of making and the evaluation of the outcome (Camere and Karana, 2017), intermediated by the organisms' growth. This temporal division breaks the flow of question and answer that normally occurs between makers and materials in crafting practices (Ingold, 2012). Therefore, designers have troubles developing the set of sensibilities that make expert craftsmen trust their intuition and know the material they work with, shaping their gestures by anticipating the effects they have onto the material. This ability to anticipate the material, i.e. "*being always a step ahead of the material*" (Sennett, 2008, p. 175), is central to learn through the process of doing and to shape ideas through making (Ingold, 2013; Sennett, 2008; Adamson, 2007; Nimkulrat, 2012). When growing a material, designers do not *feel* the effects of their making onto the material; their practices must rely on observation, as they *watch* and *look after* the organisms' growth (6.2.3). Yet, these observational moments are scarcely informative of the mechanisms governing the organism's behavior, partly because of designers' limited expertise, and partly because of the generally meagre understanding of natural systems (Sanchez et al., 2005; Alper, 1992; Hallam and Ingold, 2016). Hence, while craft is based on technical gestures and it is thus considered as the combined action of the *skillful hand* and the *sensitive mind* (Nimkulrat, 2012; Sennett, 2008; Adamson, 2007), we argue that a new set of *designerly sensibilities* (Cross, 2007) is needed to work at the intersection of design and biology. Designers will need to augment and mobilize other abilities, such as an *informed eye* and a *scientific mind*, to grasp the biological processes that take place in their experiments. In this way, the observational moments will become more transparent, allowing the material (i.e. the organism) to 'speak to them' (Petreca, 2016) and understand the organism's behaviors.

7.2. Challenging the meaning of sustainability in design and other practices

From the interview results, Growing Design emerges as a practice that hybrids crafts, science, and engineering, as also discussed by scholars (Myers, 2012; Ginsberg et al., 2014; Oxman, 2016). This hybrid nature makes designers who grow materials borrow the systematic approach of science to structure activities of *material tinkering* (Karana et al., 2015) with detailed protocols that enable the controlled manipulation of each experiment (6.2.5). Although designers couple this attitude with the intuitive approach of crafts (6.2.6), it is definitely a novel dimension that leads designers to plan each experiment ahead in multiple and controlled variants. It brings some sort of rigor to the practice of design, yet without hindering designers' creativity in finding solutions when they need to achieve specific goals. Moreover, Growing Design shares with engineering the drive for solutions that can be up-scaled (6.4.1), rather than the production of artistic, one-off pieces. As a result of its hybrid nature, Growing Design shows that interdisciplinary collaborations are needed to face the complex challenge of sustainability, and that this type of experimentations cannot be conducted through an individualistic practice, as it is, in contrast, often the case with crafting production (Dormer, 1997). In such collaborations, designers take the role of *mediators*, synthetizing and channeling the know-how of different disciplines towards a tangible product application. Growing Design thus transcends the boundaries of distinct disciplines, to achieve a truly transdisciplinary practice (Sakao and Brambila-Macias, 2018) that is aimed at tackling sustainability from a systemic perspective and at a higher and shared understanding of the problem (Section 6.3.1).

Instead of seeking for ‘drop-in’ sustainable replacement of existing technologies, Growing Design stimulates designers to mature a more radical vision on the need to shift paradigms in the production and consumption systems (Section 6.3.2). Oftentimes, grown materials are promoted as potential surrogates for more conventional, but less sustainable, options. An example is the core narrative presented by Ecovative about its trademark material, the foam-like mycelium composite, which is positioned as a replacement for expanded polystyrene (popularly known as Styrofoam). The substitution makes perfect sense: the production of polystyrene is oil-based and energy-consuming, and it is difficult to recycle because of its expanded state. On the contrary, mycelium-based composites are sustainable, fully biodegradable, shock and thermo-absorbent, thus promising a potential, cost-effective replacement for Styrofoam (Holt et al., 2012). Meanwhile, other design cases propose the application of grown materials in standard consumer products (e.g. lamp, stools, etc.). Often, these products are the result of preliminary explorations with these emerging materials, thus acting as demonstrators and explorative materializations that help designers understand the material better (Section 6.1.4). Yet, these applications do not provide any additional benefit rather than the sustainability of source material. On the downside, using grown materials for similar products might even shorten their normally long lifetime, as they carry the materials' disadvantage of a high perishability.

In both surrogate or standard consumer products cases, biofabrication is used as *“a disruptive technology, that disrupts nothing”* (Ginsberg et al., 2014, p. 41), which makes us produce and *dispose* more of what we already do. Instead, as articulated by our interviews, Growing Design pushes designers to search for an added value in biofabrication and biodesign, moving beyond the ‘drop-in’ replacement of existing materials technologies. This is sometimes reflected in designers' willingness to increase the perception of materials' value (Section 6.4.2), and question the current consumption paradigm (e.g., Faber Futures' textiles dyed by bacteria; Collet, 2013). In most cases, the added value directly emerges from the qualities of materials, through hands-on experimentation and a bottom up approach that departs from the material at hand (Karana et al., 2015). An example is in this case provided by Mogu's horticulture and gardening vases (https://www.mogu.bio/), which are made of mycelium-based composites not only to replace temporary plastic pots (such as the ones widely used in horticulture), but also because the mycelium can contribute to the plants' health and nutrition through a symbiotic and biodynamic relationship. Herein, the material provides an additional benefit, which results from unexpected and unrivalled qualities of the *alive* materials, and was found through hands-on experimentation and serendipity (Montalti, 2017). In summary, Growing Design, through its creative and material-driven practice, stimulates the definition of a new paradigm of production and consumption, one that searches for meaningful applications that can lead to a long-term change towards sustainability, beyond the ‘drop-in’ replacement of existing, unsustainable technologies.

7.3. Re-interpretation of established design activities

The hybrid nature of Growing Design also gives new meaning to consolidated design activities. Prototyping, for example, becomes an activity of simulating multiple possibilities to trigger the organism's growth in petri dishes. The act of designing products (i.e. the ‘embodiment’ phase of design process, Roozenburg and Eekels, 1995) becomes instrumental in testing the productive abilities of the organism. As a result, the products designed are often archetypical or hypothetical (Karana et al., in press), i.e. an ‘excuse’ to demonstrate the novel system of production (6.1.4). Yet, the activity that is mostly influenced by the hybrid nature of Growing Design is form-giving. When talking about the ‘form’ of their design, designers' handles are pH, moisture level and nutrients: parameters that replace others such as geometry, texture, composition. The purpose is still to achieve a specific design intention, i.e. a certain aesthetics, or an intended expression (e.g. natural, elegant), but the toolset of designers is different. Hence, *form* is understood as triggered and elicited through certain variables, rather than something that designers can specify in every detail. It is programmable only until a certain level, after which it will be mediated by the organism's response. Together with *form*, designers who grow materials are pushed to challenge the conventional definition of *nature* and *culture* (see 6.4.3). These three concepts are inseparable in Western society, where *form-giving* is conventionally defined as the act of imposing man's idea (i.e. *culture*) over raw material (i.e. *nature*), ever since Aristotle's model of creation (Ingold, 2012). Anthropological studies have extensively discussed the division between *culture* and *nature* implied by this model (see e.g. Ingold, 2000; Alberti et al., 2011). These studies argue that *form* should be rather considered from the viewpoint of both nature and culture (in both *making* and *growing*, Hallam and Ingold, 2016), as arising from the mutual involvement of making forces, materials and the environment (Oxman, 2010; Vogel, 2003; Whitehead, 1978). Through a *hands-on* approach, designers similarly come to challenge the notion of *natural* and *man-made*. When designers collaborate with living organisms, the boundaries between these two concepts dissolve to achieve higher and mutual integration. In this perspective, the role of designers changes from *imposing a form* to *eliciting a formation through* the material – which in Growing Design, happens through biological processes. This also reveals to designers the dependency of form over the ecology of material production (Ingold, 2012; Collier and Alles, 2010) and the interrelated variables. From this analysis, Growing Design appears as a *designerly* ‘way-in’ (Cross, 2007) into a deeper understanding of Nature and the principles of ecological forms, which result from the mutual involvement of man, natural systems and the environment, rather than from an abstract idea in designers' mind (Oxman, 2010). As a result, Growing Design shows how design practice, through creative engagements with the material at hand, can catalyze the re-interpretation of form-giving, man-made and Nature. In this way, design produces *knowledge* and a systemic vision that transcends the disciplines involved (Sakao and Brambila-Macias, 2018) and it is aimed at shaping materials development around novel principles of ecological production.

7.4. Toward new material meanings

Interview results have also revealed how designers establish an *intimate* relationship with the material through the process of biological growth (see 6.2.3). Similar experiences have been found also in gardening practices, but not necessarily in other crafting engagements (Goodman and Rosner, 2011). Both artists and craftsmen can indeed experience an affective bond with the material, but this is related to the sense of pride and belonging triggered by perceiving the outcome of their practices as a direct materialization of their thoughts and abilities. Instead, in Growing Design, designers experience a mixture of awe and amazement through the process of growing a material, in which making happens beyond their intervention, and *because of another form of life participating in the process*. The affective bond with the material is thus described as more intimate, and it makes designers attribute higher value to the materials as they grow (6.2.3). Moreover, by acknowledging their sensitivity to minimal changes, and even the non-linear behavior of biological organisms (Chen and Crilly, 2016), designers come into contact with a set of forces that limits their space of intervention. A seemingly large set of variables is entangled in all processes of material production, not only in the growth of materials (Ingold, 2012), but also, for instance, in harvesting and baking (see 6.2.1), glassblowing (O'Connor, 2005) or in the production of bricks (Ingold, 2012; Simondon, 2005). Yet, because these practices have been cultured and refined throughout the centuries, mankind claims a higher control over them, obscuring the complexity that undergoes these technologies. In contrast, Growing Design manifests this complexity to designers, revealing the correspondence of forces (Ingold, 2013) needed to fabricate a material and an artefact through the growth of a living organism – the biological agency, the effects of the growing environment, and so forth.

Hence, through making, designers increase their awareness of production variables and overcome a detachment caused by the industrialized system (Rognoli et al., 2015). A similar awareness of the hidden side of technology is sought in do-it-yourself and hacking practices, as exemplified by the motto *"if you can't open it, you don't own it"* (Torrone, 2006). Yet, designers are not able to fully *own* biologically grown materials, even when they *open* them, i.e. even when they engage in self-fabrication practices, because the underlying technology is a biological growth performed by Nature, whose behaviors and processes are still partly obscure to us (Sanchez et al., 2005; Alper, 1992). The only revelation that occurs in Growing Design is the heterogeneity of variables that can affect the end result, which the designers learn to acknowledge and embrace in their experimentation practices, being open-minded and opportunistic (6.3.2).

Ultimately, this revelation, together with the affective bond experienced through the growth of materials, brings designers to increase their awareness of production costs. As we discussed, it also inspires them to seek a change in social practices of consumption (6.4.2), by capitalizing on these novel fabrication processes to increase people's appreciation of materials value. To this end, designers have so far taken a bottom-up approach, investing their efforts mainly in materials experimentation and exhibiting their work with a strong focus on the storytelling component (6.2.4). They are thus primarily concerned with the fabrication of materials, as corroborated in the interview responses: *"we are still dealing with the same question (…) 'how do we work with these living systems?'. How do we move away from this question, how do we advance?"* (D8). Further opportunities will come from the deliberate exploration of an experience-driven approach to the act of growing materials and addressing the problem of materials' *fabrication* jointly with their *application* in products and *appreciation* (Doordan, 2003; Karana et al., 2015). By qualifying materials not only for *what they are*, but also for *what they do*, *what they express to us*, *what they elicit from us*, and *what they make us do* (Giaccardi and Karana, 2015; Karana et al., 2015; Manzini, 1986), designers will have the opportunity to shape material properties and design materials that influence social and cultural practices related to consumption (Giaccardi and Karana, 2015). Such an approach will then harness the full potential of the biotechnological revolution, integrating a change not only in the production system, but also in people's experience of materials and the cultures arising from them.

8. Conclusions

This paper has presented an emerging material design practice, Growing Design, concerned with the fabrication of materials from the growth of living organisms for product design purposes. In Growing Design, designers operate at the intersection of biology and design, demonstrating the role they can take in shaping novel materials development in an interdisciplinary context. While these novel fabrication technologies, borrowed from biotechnology, are being established as a promising alternative toward cleaner production, no structured study investigated so far how working with living organisms contributes to rethinking the current system of design and manufacturing. The interview study presented in this paper has been conducted with eight experts to report their perspectives on designing with living systems. Their answers revealed that Growing Design impacts the conception of the materials, process, mindset and vision involved in the practice of design, owing to the fact that Growing Design process is co-performed with a living organism. Grounding on these results, this paper discussed how Growing Design (i) brings forward the need of developing new design sensibilities to face complex interdisciplinary problems; (ii) it challenges the interpretation of sustainability in design and other practices; (iii) it radically alters established design notions, such as making, prototyping and form-giving; and (iv) settled materials meanings, such as *natural* and *man-made* are challenged to reveal novel ecological principles of production. The paper has also shown how Growing Design, taking materials as an entry point, generates knowledge that can be relevant to shape emerging materials technologies, aiming towards cleaner production. Nevertheless, we argued that integrating considerations related to materials experience will be central to harness the unique potential of these novel materials toward sustainable consumption practices.

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Appendix

List of questions asked during the interview study.

Introduction & explanation of the study purpose and structure.

Phase 1 – the material.

- Can you please describe your work with (fungi/bacteria/algae) materials?
- What is this material? How do you describe it?
- For how long have you been working with it?
- Thinking also of other materials you have worked with, which opportunities and challenges do you see in this material?

Phase 2 – the process.

- How does your design process unfold? Would you please draw it (here), while describing the phases, activities?

You can also use samples or tools and place them on the map, or show me around in your workplace.

- Let's go in detail for some specific steps of the process:

  - For exploration phase: what types of studies did you perform, and how did you structure them? Which was the starting purpose for the experimentation? How did you crystallize the process? How did you know you achieved a satisfactory result?
  - For embodiment phase: When did the idea for a product application come into the picture? How was it elicited?
  - User-experience wise, which challenges did you see in how the material is perceived by people?

- Do you investigate other people's perspective? How?

  - If you wanted to do it how would you and which type of information would you be more interested in? What results would you think would be useful for your work?

- [show spider map on designers'role] How do you evaluate yourself referring to this map?

Phase 3 – purpose.

- How do you see the future role of the designer? Which will be the next steps? Please complete a second map on how you picture it changing in the next years
- What kind of awareness and considerations has this project/material prompted you?
- How does it feel to work with this material and in this domain? How did you experience it, emotionally?
- Which are your main motivations to perform this project and work with this approach to design?
- Which ethical implications do you see in your work?
- (clarification on vocabulary, if needed) How would you describe the design phenomenon/era, which you are involved?

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